

# Boosted saturation bound in colliding nuclei

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Interaction with a nucleus in  $pA$  collisions enhances the higher Fock components in the projectile proton. Effectively, this corresponds to an increase of the hard scale of the process by the saturation momentum  $Q^2 \Rightarrow Q^2 + Q_{sA}^2$ , which leads to an increased gluon distribution function at small  $x$  (but suppressed at  $x \rightarrow 1$ ) compared to that in  $pp$  collisions. In the case of  $AA$  collisions the gluon distributions of bound nucleons in both nuclei turn out to be enhanced, i.e. to be boosted to higher saturation scales compared to  $pA$  collisions. A set of bootstrap equations relating the saturation scales in the colliding nuclei is derived and solved.<sup>1)</sup> The boosting effect has a moderate magnitude at the energies of RHIC, but becomes significant at LHC.

## §1. Modification of the gluon PDF in $pA$ and $AA$ collisions

Due to the effect of broadening a nuclear target probes the parton distribution in the beam hadron with a higher resolution, compared to a proton target, so in a hard reaction the effective scale  $Q^2$  for the beam PDF drifts towards higher values,  $Q^2 \Rightarrow Q^2 + Q_{sA}^2$ ,<sup>1)</sup> where  $Q_{sA}$  is the saturation momentum in the nucleus<sup>\*)</sup>. The projectile PDF is modified due to the selection of higher Fock states by multiple interactions. The modified gluon distribution turns out to be suppressed at large  $x \rightarrow 1$ ,<sup>2)</sup> but enhanced at small  $x$ . This is a higher twist effect. Examples of  $pA$  to  $pp$  ratios of the gluon densities in the beam proton,  $g(x, Q^2 + Q_{sA}^2)/g(x, Q^2)$ , are presented in Fig. 1 for a hard reaction (high- $p_T$ , heavy flavor production, etc.) at different hard scales.

Apparently, there is an asymmetry in the properties of colliding nucleons in  $pA$  collisions: the PDF of the beam proton is modified to a state with a higher hard scale and a larger gluon density at small  $x$  than in  $NN$  collisions. At the same time, the properties of the target bound nucleons remain unchanged, because they do not undergo multiple interactions. This feature is illustrated pictorially in the upper part of Fig. 2. The picture in the bottom part of this figure demonstrates that in the case of a nuclear collision, the PDFs of bound nucleons in both nuclei are drifting towards higher parton multiplicities. The new scales depend on each other: the higher is the saturation scale in the nucleus  $A$ , the more is the shift of the saturation scale in the nucleus  $B$ , and vice versa.

Such a mutual influence of the scales can be described by bootstrap equations,<sup>1)</sup>

$$\tilde{Q}_{sB}^2(x_B) = \frac{3\pi^2}{2} \alpha_s(\tilde{Q}_{sA}^2 + Q_0^2) x_B g_N(x_B, \tilde{Q}_{sA}^2 + Q_0^2) T_B;$$

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<sup>\*)</sup> We assume that the coherence time of gluon radiation substantially exceeds the nuclear size.

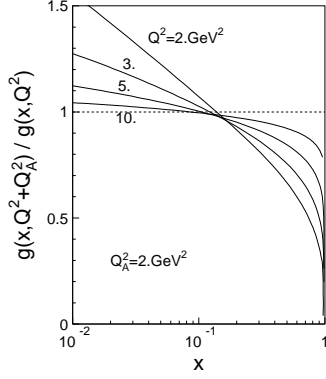


Fig. 1. Ratio of the gluon distribution functions in the proton in  $pA$  and  $pp$  collisions calculated with MSTW2008<sup>3)</sup>. The saturation momentum  $Q_{sA}^2 = 2 \text{ GeV}^2$  and hard scale  $Q^2 = 2, 3, 5, 10 \text{ GeV}^2$ .

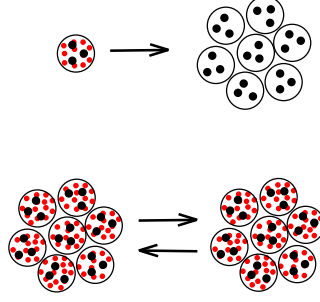


Fig. 2. *Top:*  $pA$  collision in which the colliding proton is excited by multiple interactions to higher Fock states which have more small- $x$  gluons. *Bottom:* nuclear collision in which participating nucleons on both sides are boosted to a higher saturation scale.

$$\tilde{Q}_{sA}^2(x_A) = \frac{3\pi^2}{2} \alpha_s(\tilde{Q}_{sB}^2 + Q_0^2) x_A g_N(x_A, \tilde{Q}_{sB}^2 + Q_0^2) T_A. \quad (1.1)$$

Here  $x_{A,B}$  are the fractional light-cone momenta of the radiated gluon relative to the colliding nuclei,  $x_A x_B = k_T^2/s$ ;  $Q_0^2 = 1.7 \text{ GeV}^2$  is chosen to get the correct infrared behavior. These equations lead to a larger nuclear saturation scale  $\tilde{Q}_{sA}^2$  in  $AA$  compared to  $Q_{sA}^2$  in  $pA$  collisions.

The solution of equations (1.1) for  $\tilde{Q}_{sA}^2$  in a central lead-lead collision at the mid rapidity is plotted as function of nuclear thickness  $T_A = T_B$  in the upper panel of Fig. 3 at the energies of RHIC and LHC, and the ratio  $\tilde{Q}_{sA}^2/Q_{sA}^2$  is shown in the bottom panel. While the magnitude of the boosting effect is moderately large, about

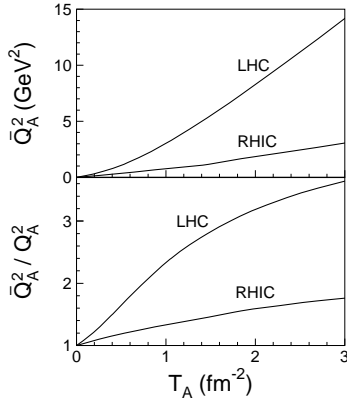


Fig. 3. *Top panel:* The boosted values of the saturation momentum squared  $\tilde{Q}_{sA}^2$  calculated at the energies of RHIC and LHC as function of nuclear thickness  $T_A = T_B$ . *Bottom panel:* the ratio  $\tilde{Q}_{sA}^2/Q_{sA}^2$  as function of  $T_A = T_B$ .

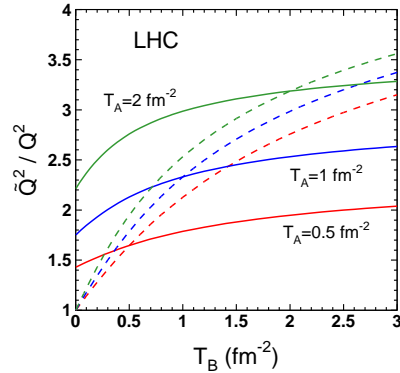


Fig. 4. Solutions of the reciprocity equations (1.1) for non-central collision of identical nuclei  $A$  and  $B$  at  $x_A = x_B = 0$ . Dashed curves correspond to  $\tilde{Q}_{sA}^2/Q_{sA}^2$ , the solid curve to  $\tilde{Q}_{sB}^2/Q_{sB}^2$  as function of  $T_B$ . In both cases  $T_A$  is fixed at 0.5, 1.0 and 2.0  $\text{fm}^{-2}$  from bottom to top.

20% at the energy of RHIC, it becomes significant at LHC.

In non-central collisions  $T_A \neq T_B$  and the solution of equations (1.1) is presented in Fig. 4 separately for  $\tilde{Q}_{sA}^2/Q_{sA}^2$  (solid curves) and  $\tilde{Q}_{sB}^2/Q_{sB}^2$  (dashed curves). For each set of curves  $T_A$  is fixed at 0.5, 1 and  $2 \text{ fm}^{-2}$  from bottom to top.

## §2. Observables for the boosting effect

Since the nuclear medium in  $AA$  collisions has an enriched gluon density at small  $x$ , it is more opaque for color dipoles than what one could expect extrapolating from  $pA$ . In particular, charmonium suppression by initial state interactions (ISI) should be stronger.<sup>4)</sup> The modified dipole-nucleon cross section is also subject to the boosting effect,

$$\tilde{\sigma}_{dip}(r_T) = \frac{\tilde{Q}_{sA}^2}{Q_{sA}^2} \sigma_{dip}(r_T). \quad (2.1)$$

The magnitude of the ISI suppression of  $J/\Psi$  in central  $Pb-Pb$  collisions as function of impact parameter  $\tau$  is presented in Fig. 5 by dashed (no boosting) and solid (magnified by boosting) curves. Again, the boosting effect is rather small at RHIC,

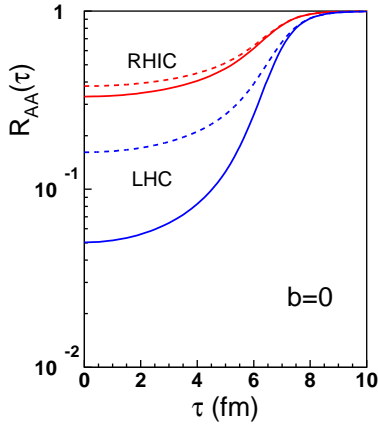


Fig. 5. Initial state suppression of  $J/\Psi$  produced in central  $Au-Au$  collisions at  $y = 0$  as function of impact parameter  $\tau$ . The upper and bottom sets of curves correspond to  $\sqrt{s} = 200 \text{ GeV}$  and  $5.5 \text{ TeV}$  respectively, and are calculated excluding (dashed) and including (solid) the boosting effect.

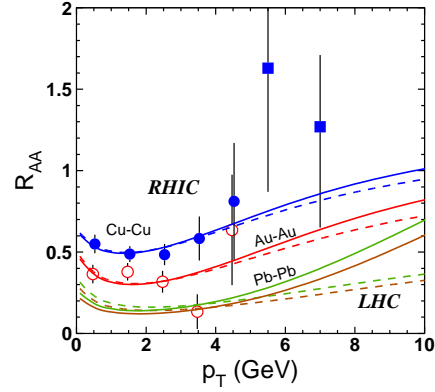


Fig. 6. Data<sup>8)-10)</sup> for the nuclear modification factor  $R_{AA}$  for  $J/\Psi$  production in central  $Cu-Cu$  collisions (closed points) and  $Au-Au$  (open circles) at  $y = 0$  and  $\sqrt{s} = 200 \text{ GeV}$  (RHIC). The bottom set of curves show  $R_{AA}(p_T)$  predicted at  $\sqrt{s} = 5.5 \text{ TeV}$  (LHC). Dashed and solid curve are calculated excluding, or including the boosting effect, respectively.

but is significant at the energy of LHC.

Unfortunately, most of the effects related to ISI are masked by final state interactions (FSI) of the  $J/\Psi$  with the created dense medium. So it is very difficult to approve or disprove the boosting effect at the energies of RHIC, at least with the current precision of  $J/\Psi$  data. However, the large magnitude of the boosting effect expected at the energies of LHC, make it plausible to single out the effect from  $J/\Psi$  data. As far as the broadening of the mean transverse momentum squared, which is

given by the saturation momentum,<sup>5)</sup> increases from  $Q_{sA}^2$  to  $\tilde{Q}_{sA}^2$ , the Cronin effect should become much more pronounced. This is demonstrated in Fig. 6 on the example of the  $p_T$  dependent nuclear ratio  $R_{AA}(p_T)$  predicted for  $J/\Psi$  produced in gold-gold collisions at RHIC,<sup>6)</sup> and in lead-lead at LHC.<sup>7)</sup> The result of calculation either with, or without the boosting effect agree with data<sup>8)-10)</sup> at  $\sqrt{s} = 200$  GeV. The suppression of  $J/\Psi$  by FSI is calculated with the transport coefficient  $\hat{q}_0 = 0.6$  GeV<sup>2</sup>/fm, which was adjusted<sup>6),7)</sup> to describe the data. At  $\sqrt{s} = 2.7$  TeV the nuclear ratio for lead-lead is predicted using the value of the transport coefficient  $\hat{q}_0 = 0.8$  GeV<sup>2</sup>/fm found in the analysis<sup>11)</sup> of data on suppression of high- $p_T$  hadrons. The boosting effect at  $p_T > 5$  GeV is strong, so may be seen even with not a very high statistics.

Another sensitive probe for the boosting effect would be an observation of different magnitudes of broadening of  $J/\Psi$  in  $pA$  and  $AA$  collisions at the same path length in the nuclear matter.<sup>1)</sup> Indeed, broadening is related to the dipole cross section,<sup>12)</sup> which is enhanced by the boosting effect, Eq. (2.1). While RHIC data are not able so far to discriminate this weak effect, this task looks solvable at LHC.

Also the hadron multiplicity is expected<sup>13)</sup> to correlate with the saturation scale, so we expect a mismatch between the hadron multiplicities measured at the mid rapidity as function of centrality. Indeed, an indication at such a break was observed at RHIC,<sup>14)</sup> but the effect is rather small, more precise data are required.

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